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Natick Soldier Research, Development and Engineering Center NSRDEC

PowerFilm PowerShade Fixed Site Solar System Cost Reduction Plan

Final Report on
Contract No. W911QY-12-C-0091
(PowerShade Fixed Site Solar System)

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Executive summary

Power film and its partners have developed a Generation II PowerShade which meets or exceeds the goals of this development contract, increasing power and improving the ROI of the power shade significantly while improving a number of the human factors. Comparing the Gen II 1.8 KW PowerShade to the equivalent power Gen I unit (Gen I Medium), The cost has been reduced from \$38,000 to \$28,000 or by 26.3%. This is as compared to the Threshold goal of 20% and Objective of 30%. Output power per unit area increased 36% from 2.04W/ft2 to 2.78W/ft2 compared to a Threshold goal of 10% and Objective of 20%. The Specific Power (KW/lb) increased 74% from 3.9 W/lb to 6.8 W/lb. While the weight reduction per Watt was not a stated goal, it is an important metric for usability. Lifetime has been increased from 3 years to the objective of 10 years. When all these improvements are taken into account and the PowerShade is used in optimum conditions, the crossover point relative to diesel generators comes at approximately \$3.61 cost for the diesel fuel. This would give the PowerShade a positive return on investment for a wide range of installations.

Improved functionality of the PowerShade includes field replaceable modules. Poles were improved to make handling easier and the weak spot of top pole pins was overcome. The wiring harness was moved to the top of the PowerShade, thus making wiring during deployment far easier and putting the harness in a location where it would not be snagged while assembling and raising the tent.

A new battery operating system was designed which adds capability of grid tie connection to the standalone function. This battery operating system has built-in intelligence which can signal a generator to start and pick up the load when batteries are low and turn the generator back off as the batteries get full.

A number of improvements in manufacturing technology were developed which are expected to reduce costs of producing the PowerShade in higher volumes. Automatic taping and laminating feed facilities were designed and built to improve quality and take out a significant amount of handling in the submodule preparation process.

Introduction

Figure 1. PowerFilm's Generation I Medium PowerShade

PowerFilm's forward deployable PowerShade structure (figure 1) was developed to provide power from solar energy to tactical units in an operational environment and reduce heat load on the structures it covers. The Generation 1 (Gen I) PowerShade did this very successfully, reducing the heat load on covered tents by up to 30%, and thus decreasing the air-conditioning load by 30%. Simultaneously, the PowerShade provided power for operations. However, in this era of constrained resources it was necessary to implement cost reduction steps on the PowerShade.

The price points of the PowerShade are driven by a number of factors including fabrication cost. This program's goal was to reduce the life cycle cost for the PowerShade to a level which makes financial sense to the user while at the same time enhancing deployability and capability to increase the return on investment.

There were three main aspects which could be improved or modified to reduce the life cycle cost. The first factor is the lifetime of the PowerShade itself. The initial design criteria was set at three years lifetime in the field. The life-cycle costs could be reduced significantly when this lifetime is increased to ten years. The photovoltaic modules on the power shade already have an estimated lifetime of twenty years so, a key aspect of this performance goal had already been met. It is the fabric and mechanical bonding components of the unit which limited its lifetime. A major component of this program was identifying fabrics and manufacturing methods which allow the tent structure to survive for ten years in the tactical and operational environment.

The second aspect that impacts life-cycle cost is the base manufacturing expense of the structure. The PowerShade is a complex structure and needed more done to minimize the manufacturing expense. Fabric and pole designs were areas with significant opportunity for cost reduction in the manufacturing process through modified design and improved manufacturing processes and flows. Improving the performance of the photovoltaic has the same impact by effectively increasing the amount of power provided per unit of area, thus reducing the life-cycle cost in terms of dollars per kilowatt hour.

The third aspect impacting life-cycle cost is the efficiency of utilization of the power coming from the PowerShade. The original Balance of Systems (BOS) unit, which takes power from the PowerShade and stores it in the battery before putting it into an inverter to provide AC power, is the first generation of this type of unit. Much has been learned over the years in terms of both systems design and operating parameters which could significantly boost the percentage of the power collected that actually goes into useful work.

Overall Performance of the Gen II PowerShade relative to the Gen I PowerShade

Many elements of the PowerShade were fully redesigned for Generation II. This includes moving to double wide panels, 24 V operating voltages which improve the overall power available significantly. The table below shows a comparison between Generation I and Generation II performance parameters.

Structure	Nominal power	Small volume price	Dollars per watt	Weight	Watts per pound	Top surface area
Gen I, medium	1.8 KW	38,000	21.11	462	3.9	880
Gen II, 1.8 KW	1.8 KW	28,000	15.55	265	6.8	648
Gen II 3.6 KW	3.6KW	54,000	15.2	493	7.3	1296

Tent and module design
There are many aspects of the redesign. The sections below describe the reasoning and outcome of the main areas.

Fabric choice. Gen I used a PVC jacketed Polyester fabric. Even with additives, the PVC coating is susceptible to UV degradation which limited the tent's lifetime. It was also relatively heavy with high tack, making it somewhat difficult to handle. We searched for alternative fabrics to solve these issues.

We ended up choosing an HDPE weave (Architec 400). This type material has a proven lifetime of well over 10 years and there is field use experience in the Army (light weight solar shade). The standard solar shade exhibited a charge build up which rendered it unsuitable for deployment over ammunition. We put the same restrictions on the Gen I PowerShade and this unit until proven otherwise in field tests. The module coverage on the surface and wiring harnesses may mitigate the problem entirely. The weight is 12oz/yd as opposed to 18oz/yd for the PVC/polyester fabric. In addition to being slightly lighter, the fabric is "slipperier" and slides over itself more easily than the PVC coating which makes it much easier to handle large sections on the ground. The main disadvantage is that it can't be RF or thermal weld bonded like the PVC. All seams on this fabric must be sewn. This adds some cost back into the system, but is well worth it for the lifetime gain. Figure 2 shows a comparison of critical parameters for the 3 lead fabrics evaluated.

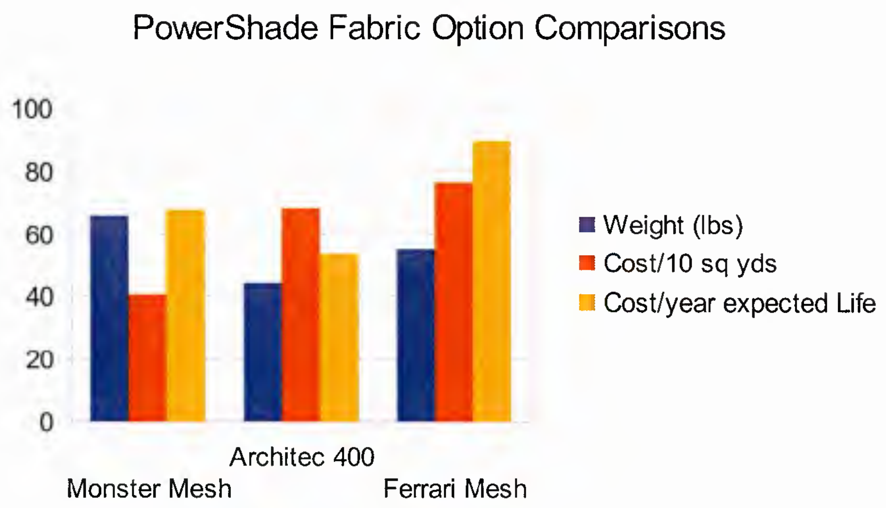


Figure 2. Fabric comparisons. To allow a baseline comparison, the weight and ($) cost per year of expected life are based on the quantity of fabric needed for a small Gen I PowerShade.

Sub-module design. The Gen I PowerShade had a lot of top surface area taken up in the open space between modules. Each module was approximately 13" wide. A range of folding and packing options were evaluated on the Gen I unit and it was found that folding between pairs of modules was at least as effective as folding between each module. The stack folded in this way was twice as wide but half as

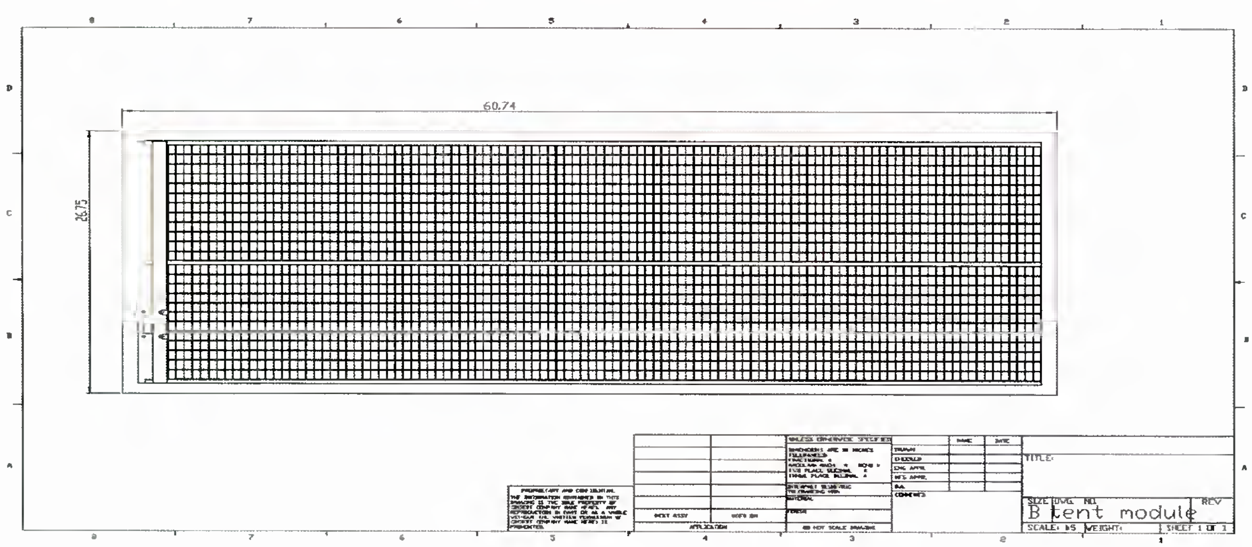


Figure 3. PV Module design drawing for the Gen II PowerShade.

high. The 27" width was quite acceptable for packing in a diaper and crate.

Based on these results, we pursued a new module design which used two 13" wide strips of PV material laid out side by side and connected in series. This configuration allows for a significant increase in effective packing density. We settled on an optimum size for these sub-panels and used that as the basis for the design and layout of the top fabric sections. From there we could redesign the overall tensile structure. Figure 3 shows the final module design.

Sidewall design. Observations of the Gen I structure indicated that the sidewalls, as initially designed, added significantly to the weight and side wind load on the structure without providing a strong benefit. A tensile analysis was done for variations of the height of the sidewall arch. A height was chosen which maintained full mechanical strength integrity while minimizing the sidewall surface area.

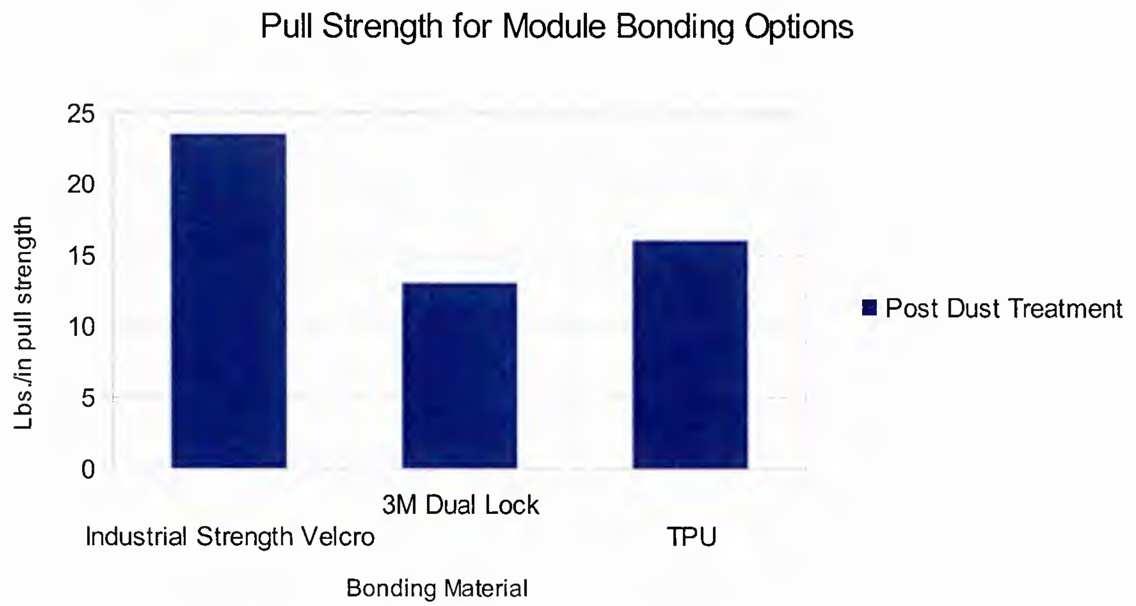
Module mounting. On the Gen I unit, modules were thermal bonded directly to the fabric before the fabric sections were cut out and sewn together to create the tent. This had a certain manufacturing elegance and benefit, but also had some serious drawbacks. A major drawback was that the modules were not removable and replaceable in the field. A second major drawback was that the fabric could not stretch to accommodate stresses where it was bonded to the module. this caused high tension to be focused at the corners of the module and delamination failure could occur. A third drawback was added difficulty in handling the fabric with the modules attached during the tent fabrication process.
A number of options were investigated to solve these problems. One prime candidate was laminating the modules to a fabric backing leaving a stretchable border around the modules. The outside edges of the fabric would be attached to the main tent fabric, allowing the two layers to move independently, thus relieving tension. The second prime candidate was to sew pocket frames onto the main tent fabric. The underside of the frame fabric had Velcro which could lock onto matching Velcro on the front perimeter of the modules. In this case, the module layer and underlying tent fabric layer could move independently to relieve stress.

A major benefit of using this frame method is a significant simplification of our manufacturing process. In our Gen I approach we had to laminate modules onto rolls of fabric which were then shipped to the tent fabricator who processed them into the finished tent structure and then shipped that structure back to us for mounting junction boxes and wiring harness. Only then could we ship the finished product to the customer. With frame mounting, the tent fabricator can work independently and send a completed unit us. We can then attach modules and wiring harness and ship the competed unit on to the customer. This can reduce time delays and expenses in shipping as well is making each organizations manufacturing more straightforward.

Fabricating the structure with modules already attached to the fabric required special care by the tent maker and a high level of specialized training. It limited acceptable handling techniques to some that were more time-consuming and expensive. In a similar way, attaching the junction boxes and wiring to a finished tent was a fairly difficult process at PowerFilm which is now avoided..

An added benefit of this sequential processing is easing of difficulties relating to inventory. The tent fabricator can inventory materials and components that will go to directly into the fabricated structure. They need nothing from PowerFilm in order to do this. PowerFilm can inventory modules which go into the structures without worrying about their combination with fabric.

One uncertainly in this approach was possible failure of the attachment because of dust build up in the Velcro. To simulate the intrusion of dust similar to that present in Afghanistan, a 50/50 mixture of 4 and 10 micron SiO_2 dust was prepared and suspended in propanol such that the dust comprised 50 % by volume of the total mixture. Using a squirt bottle, this mixture was forced into the bonding interface of 2 foot long by 1 inch wide sections both industrial strength Velcro and 3M Dual-Lock. Following saturation with the dust solution, the test sections were strung into a test rack on the back of a pickup truck using rubber straps to hold them under moderate tension with 10 lbs of lead shot hung from them. This test setup was then driven on a mix of highway and gravel roads at speeds ranging from 10 to 65 mph resulting in significant wind flutter in the fabric and large bounces (up to 8" up and down movement) from the road. This test was carried out for 1 hour in to roughly simulate stresses on the bond before doing a pull test. Following the road test, a 1 inch sample of the bonding material was tested on the Instron. The bond strengths measured were 23.5 lbs/in for the industrial strength Velcro, 13 lbs/in for the 3M Dual-Lock, and 16 lbs/in for the TPU. Costs for the three bonding options were also compared, with the industrial strength Velcro being the cheapest and the 3M Dual-Lock being by far the most expensive. Both bond strength and costs shown in the charts below in figure twelve.



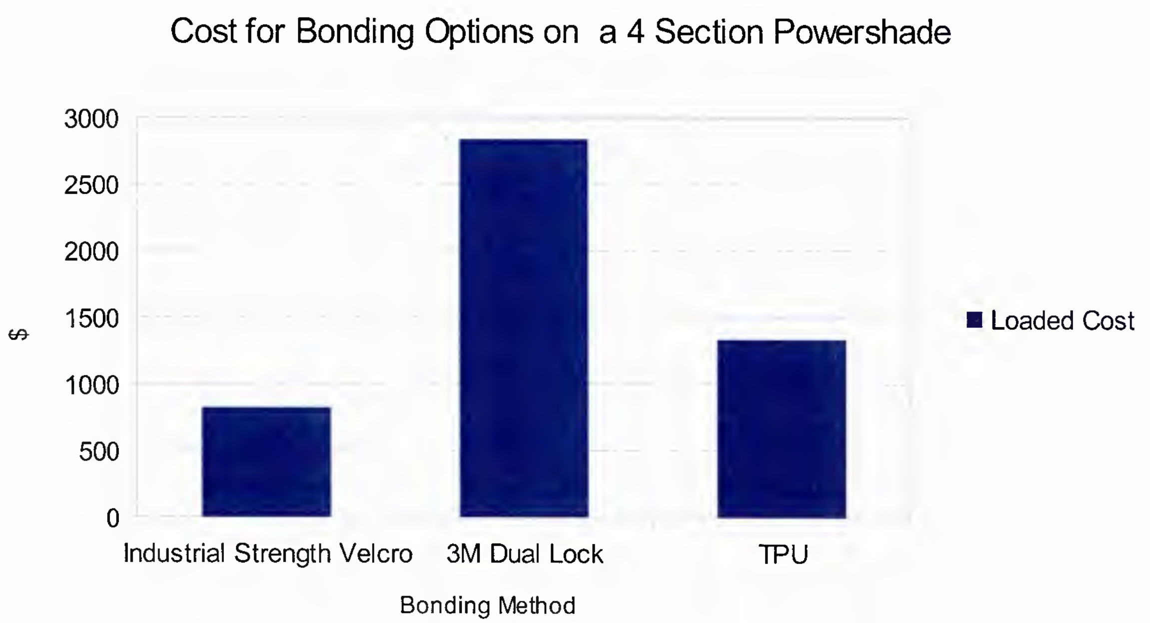


Fig 4. Pull strength and cost graphs

We have gone forward with this design option on the basis of flexibility in fabrication and replacement. Figure 5a shows a fabric strip with Velcro which forms one side of such a framed mounting approach. Figure 5b shows a row of modules attached in this manner to a prototype tent section.

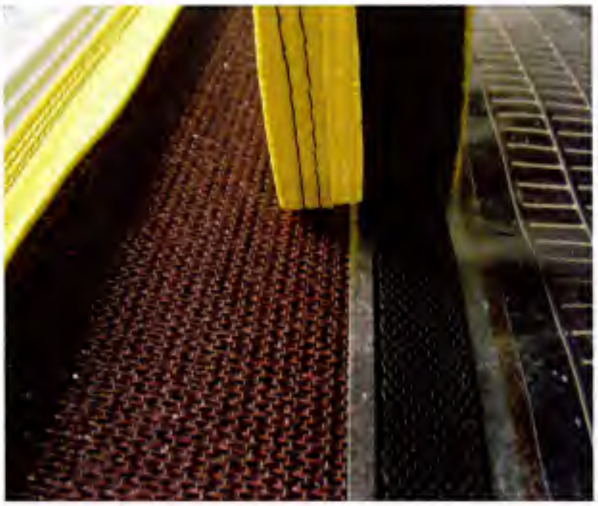


Figure 5a. Photo demonstrating attachment method with sewn fabric strip (yellow) peeled back to show Velcro. matching Velcro is shown on the perimeter of the module.

Figure 5b. Modules mounted on a Gen II PowerShade section using the Velcro frame method.

Wiring harness and voltage Trades were evaluated for a 24V system versus the 12 V system in Gen I.

Key advantages identified for moving to 24V were:
1. Lower current which allows smaller gauge copper wire. This reduces both cost and weight.
2. By linking adjacent modules to build voltage to 24 V, fewer connectors to the working harness are needed which reduces cost and complexity.
3. The wiring harness and electronics tend to run more efficiently and with lower resistive loss at 24V and lower current.
4. A wider range of standard COTS inverters is available at 24 V relative to 12V input.

Drawbacks to the 24 V system included:
1. The 24V nominal voltage modules can have open circuit voltages around 44V. this put more limitations on the input semiconductors for the electronics and tends to move them to a slightly higher cost point.
2. The safety assessment has to be reconsidered for the higher voltage.
3. Using two sub-modules in series increases the potential losses from shadowing or current limitations from panels at different angles to the sun.

The cost and weight advantages of the 24V system drove the choice. Current limitations from shadowing and angle variations were found to be small.

The pocket for the wiring harness was successfully moved to the top of the tent structure. This makes connections to the working harness during installation much easier for the soldier and reduces the rick of snagging the harness on ground objects when sliding the tent sections around during installation.

Pole development The poles have been fully redesigned, starting with an analysis of the requirement. The Gen I poles were over designed, which had negative impact on cost, weight, and handling properties in the field. Models were created both by a group at the Naval Underwater Warfare Center and by Solar Shade USA. These were correlated with actual compressive force measurements taken at the Naval Underwater Warfare Center.

Materials considered included Steel, Aluminum (Gen I was Al), and carbon fiber composite. The carbon fiber was quickly eliminated based on cost. Aluminum and steel were both workable and had a number of trade-offs. The strength of the steel allowed thinner wall tubing, but the lighter weight of the Al allowed thicker walls and equivalent strength at roughly equivalent weight.

Two main factors drove the choice to steel. The first was cost. Standard steel tubes are available in a vast array of sizes which allowed use of high volume manufactured product instead of having a custom die fabricated to extrude the needed Al sizes. The second is that the steel poles of the needed strength could be made with smaller diameter which are easier for a hand to get a grip on. This should make handling easier during set-up.

Figure 6 shows our finished pole design while figure 7 shows a close-up of the removable cap with pin. The original poles had a fixed Aluminum pin that locked into holes in the PowerShade top. Field experience showed these to be a weak point, subject to fatigue and failure. Repair was difficult. The new design has steel pins which have been shown to be much less subject to fatigue, and are easily replaceable if they do fail.

Figure 6. Full pole assembly

Figure 7. Close-up of removable pole top fitting with

pin. This component is easily replaceable if damaged.

Module layout

With the module design and mounting method established, we could move forward with module layout and final tensile structure design to allow the most cost effective usable system. As was one with the poles, a finite element analysis program was used to provide guidance in the fabric design and establish the required strength of the fabric elements.

Figure 8 shows the final layout of modules on a 3.6 KW tent top while figure 9 shows the prototype 1.8 KW structure erected. Other elements which played into the choices of layout and sizes were cost effectiveness of fabric and solar module utilization. This is essentially choosing dimensions which create minimum scrap material in the fabrication process.

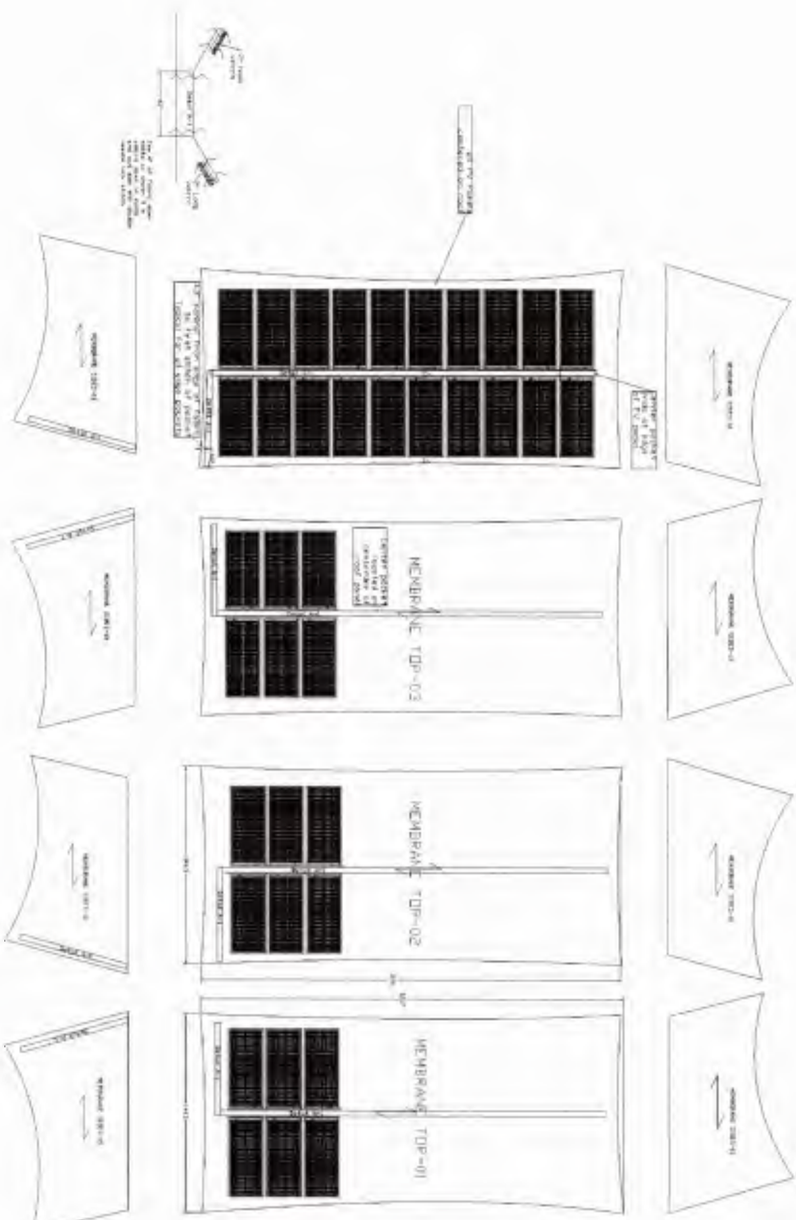


Figure 8. Fabric sections and module layout for a 3.6 KW Gen II PowerShade

Figure 9. Picture of the 1.8 KW Gen II PowerShade prototype.

Alternative stacks for fire retardancy Previous work on panels very similar to those going into the PowerShade had shown that there was potential issue if the panels were ignited from an external flame source from the front side. Specifically the adhesive between the front ETFE face and the PV module was prone to igniting and was capable of producing a significant quantity of flaming drops. In an effort to address this issue two major approaches were developed to potentially improve flame resistance: 1) The addition of Craneglas (Craneglas is a non-woven fiberglass mat available in various thicknesses) to the adhesive layer which would hold the adhesive in a matrix to prevent drips and 2) Casting a PVDF film into the Craneglas in hopes that the Craneglas would hold the non-flammable PVDF in place to prevent air from reaching the flammable adhesive for a fully flame retardant stack.

In order to develop the fully flame retardant stack, Roland Technologies, a specialty films company, was contracted to work on casting PVDF into Craneglas. Initial samples of the concept were done in house using a vacuum laminator at a high enough temperature to begin flowing the PVDF into the Craneglas. Using this method it was possible to get a module with a power reduction relative to normal laminates of just under 4%, and it was hoped that by directly casting PVDF at full flow it would be possible to better saturate the fibers of the Craneglas, achieving both a more thorough penetration into the Craneglas and better transmission. Roland did some small patch sample which looked to show promise, and then ran 10,000 yards of material on their line working with coating parameters as they ran to maximize penetration into the Craneglas. Unfortunately, even the best material they were able to make on the line did not even match the optical transmission of the vacuum laminated samples. Given the total unsuitability of the material as a solar encapsulation, the full flame testing was not done, and no fully flame retardant PV module was able to be made.

Craneglas saturated with TPU was found to completely eliminate flaming drops when ignited with a torch, but have no significant impact on flame spread. It also reduced power from the laminated module by less than 0.5%. Significant work was done to make this stack manufacturable so as to at least eliminate the greatest aspect of flame threat even if full fire retardancy could not be achieved. Work with outside vendors to combine the Craneglas and TPU was unsuccessful, with none of them being able to provide a thorough saturation of the Craneglas necessary to achieve good optical transmission. In house development was able to work out a process using 64" roll laminators to process laminates up to 30" wide at ~2'/minute, which is useable for processing. Due to the fact that there is no way this material will pass full flame testing, no testing beyond the in-house testing to verify the elimination of flaming drops was performed.

Future work indicated: Looking past the development and evaluation of the alternative lamination stacks called out in this task and based on the failure of these to fully control the flame spread, we looked at other paths forward which might solve this issue. One possible option found was a clear flame retardant spray. Tests using this and other potential flame retardants in combination with the Craneglas will continue to be worked on as ongoing improvement work on the PowerShade. As of the conclusion of this contract Natick is doing initial flame testing on test sample created using this flame retardant spray added to the Craneglas layer in order to provide feedback for further future development.

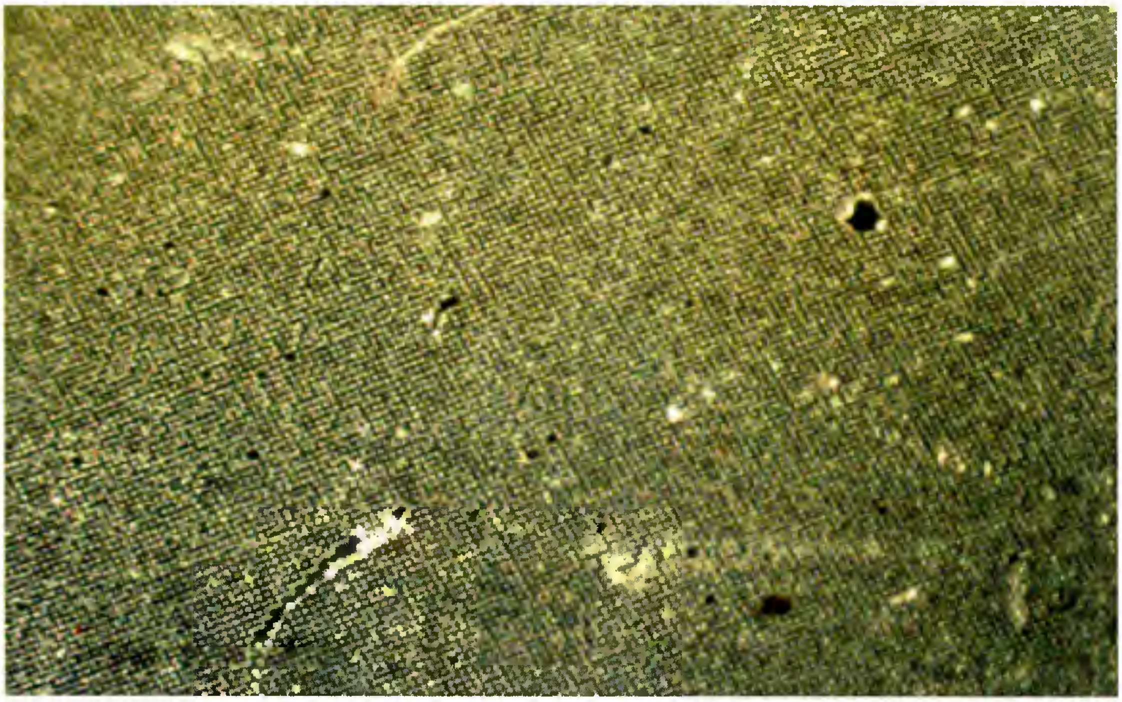
Performance improvement effort

Three R&D Efforts were aimed at improving performance of modules. One was an effort to improve short circuit current through insertion of a textured transparent polymer layer between the metal and silicon layers in the device to improve back scattering and reduce absorption in the metal. The second effort was a layer to improve voltage on devices. Various offshoot directions suggested by results in these experiments were also pursued as described below. The third effort was to reduce silver usage by either lowering silver content of the conductive ink or printing interconnect patterns which require less ink.

Scattering by Inserted Polymer Layer From quantum efficiency (QE) measurements, it is known that there is light in the red and near IR region of the spectrum which is not current absorbed but which could be collected. If collected, this could add up to 20% to the device current. A method which could scatter light within the absorber layer of the PV without causing other problems would allow capture of a good portion of this light. A concept for improving this light collection, which might have also reduce shunt leakage was to insert a textured polymer layer between the back metal and the N+ silicon layer. The texture would be of a size and form to refractively scatter light so that it reflected off the back metal at an angle which would increase the path length in the silicon and thereby enhance absorption. The thinnest points in the texture would allow intimate contact between the N+ silicon and metal layers, creating a point contact system. Any defect which might cause a shunt would have a reduced effect unless it was aligned with one of the point contacts. This system would significantly reduce shunt leakage and improve production yield. A potential drawback is that series resistance may increase. The density and size of the point contacts would be optimized to balance shunt leakage and series resistance.

Fabrication of a coating machine capable of applying this type of patterned polymer layer was completed. Initial work was done using a UV curable polymer material.

Modules were completed and testing done on samples using imprinted polymer layer between metal and Silicon which used pyramidal shaped holes for contact between those layers. These were done with a variety of shapes and layer fabrication processes. An image of one such polymer layer on the Al substrate is shown in Figure 10



IV curves were taken on respective experimental and standard reference modules to determine effectiveness. The series resistance is a bit higher for the test sample indicating that the contact area is insufficient for carrying the required current without loss. This is not unexpected, as the contact geometry was not optimized. Changing the percentage of open area at the base of the inverted pyramids would be a rather straightforward fix for this issue.

The voltage was also lower, which most likely is caused by a reduction in built in potential at the back of the bottom cell. This could be an interface effect difference between the Al/Si interface vs an Organic Polymer/Si interface or a reduced doping efficiency of the n+ layer due to contamination from the organic layer. In either case, this issue could likely be solved with insertion of an appropriate barrier layer such as TiN.

The discouraging result of these test is that the Short circuit current (Isc) has gone down rather than up. This argues against our base theory that the interstitial layer, by improving the optical index transition between layers, would reduce parasitic absorption of red light in the back Al layer and therefore improve reflection of red light thus improving Isc. To investigate this further, we ran IV curves with extra red light. The Isc improves with this extra light, indicating that we are still starved in that region, so have not gotten the effect we were seeking. Our conclusion is that the interstitial layer must be adding more red light loss mechanisms than it is gaining with the theoretical optical index matching. These results led us to abandon this line of pursuit.

P+ silicon/transparent conductive oxide interface layer Because the top layer of the PV stack is a P-type material and the transparent conducting oxide, TCO, is an N-type semiconductors, there is a voltage loss at the interface of these two layers. Since the function of the P-layer is to provide a bias voltage for charge separation from the PV and the TCO is for current collection, this bias serves only to decrease the efficiency of the PV device.

To minimize the voltage loss at this interface, an ohmic contact is preferred which can be obtained by providing for carrier recombination. This can be done by using a metal at this location.

Additionally, optical losses occur at these layers that prevent the incoming light from generating electrical carriers and is due to absorption in the P-layer and is a factor of the dopant concentration. Minimizing the dopant to a minimally acceptable level will improve the performance of the PV. Alternatively, increasing the electronic band gap of the P-layer would make it more transparent to the light wavelengths used by the PV material. Substituting carbon for some on the silicon would provide for this option.

Copper and silver were both investigated as an interface material between the P-layer and the TCO. These were selected for their conductivities and their abilities to form extremely thin layers and nano-sized islands that would not impede the passage of light. Thin layers were applied to clear coupons and to the interface of PV devices which were subsequently measured.

It was found by the optical measurements that anytime these materials were present, at any level or thickness, there was an optical loss. Additionally, that whenever these materials were applied to the interface, again at any level, the efficiency of the PV was reduced.

Finally, there was no improvement in the voltage of the PV devices, indicating that this technique is not applicable for this task.

A series of test optimizing the silane (silicon source), and diborane gas, (P-type dopant source gas), flow was performed. Because the flow for the diborane is small compared to the silane, a special flow controller and a lower concentration gas source were used.

It was found that the current quantity of silane gas flow was adequate and that the diborane, while higher than necessary, showed no benefit having been reduced. However, it was found that the overall quantity of diborane can be reduced, allowing for the use of large flow mass flow controllers with a lower concentration source gas without detrimental effects to the PV performance. This is significant because mass flow controllers that are rated for higher flows have been found to be easier to work with, resulting in a higher consistency product.

Carbon was added to the P-layer using an acetylene gas sources, 5% in Helium. This gas was plumbed directly into the silane supply line for the P-layer deposition zone, allowing for complete mixing. PV modules using acetylene flows from 0 to 50% of the silane flows were produced and tested.

It was found that the addition of acetylene to the P-layer process gases did not improve the performance of the PV indicating that the band gap was not affected by this test.

Alternative conductive grid inks The silver ink is used to collect the PV generated current from the top side of the modules. The goal concerning alternative conductive grid inks was to reduce the cost of the silver ink layer without a reduction in PV power with experimentation taking two paths. The first path was identifying a cheaper ink material; the second was to reduce the amount of silver used per module.

A number of alternative ink materials were identified including: silver plated copper flake, tin/silver mixture (80:20), carbon/silver mixture (50:50), nickel, and self assembling silver nano-particle grid. These materials were chosen due to the potential cost savings in silver content. Each of the inks were required to pass a number of tests: maneuverability in our process, ink layer adhesion, equivalent module power, damp heat stability, process variability, module life time, and cost.

- The self assembling silver nano-particle grid failed due to lack of adhesion to the silicon PV substrate and poor light transmission resulting in low module power.

- The carbon/silver inks were determined by the manufacturer to be more expensive than our standard ink due to extra processing costs.

- The nickel ink never materialized out of the development department from the manufacturer.

- The tin/silver mixture failed due to degradation of module power (lower conductivity ink).

- The silver plated copper flake was the most promising ink, but ultimately failed due to manufacturability in our process. The silver plated copper clogged our rotary screen during printing even short distances. The ink manufacturer was unable to solve the particle size, rheology, and/or solvent issues.

Contact with ink vendors will continue, but there has not been a change in production to any alternative inks.

Reducing the amount of silver used per module was more successful. The silver ink is applied to the module using screen printing systems. A number of tests screens were made to reduce the amount of silver ink used in different areas of the silver screen including: bus bar, weld lines, finger height, and total number of fingers. These experiments lead to the creation of the “hairy” finger pattern which reduced the contact resistance of the ink with the PV cell. It was found that “hairy” fingers allowed for fewer fingers (silver savings), and still increased module power (6.6% higher versus average production). Additionally, the amount of silver required was reduced in the bus bar and the weld line areas. The total silver ink reduction achieved was about 50%. After an eight roll trial, the down-web material production line has been transitioned completely to “hairy” fingers, dashed weld lines, and perforated bus bars.

Manufacturing technology and automation

The new configuration of modules using two strips of PV material laminated side by side is a moderately complex assembly task. It is however suitable to automation which can bring the cost down significantly. The approach to automating this process uses a number of steps which each require a specific hardware operation. First, modules must be sheated from roll and laid out in proper side-by-side position. Second, busbar tape must be placed on the modules to allow connections and to connect the two strips in series. Third, a PC board which allows mounting of the junction box must be placed and soldered to the busbar strips. Fourth, the assembled module must be fed in to the roll lamination system with proper spacing to allow efficient use of encapsulate and make die-cutting relatively easy. Machines to accomplish these goals were designed and constructed under these projects and are described below.

Parallel Taping Machine To keep costs under control for fabricating double wide modules that are compatible with our new tent design, it was necessary to design and build a set of new automated manufacturing tools that are capable of high throughput and minimum labor expense. The first of these tools is referred to as the "Taper" and has the function of taking strips of raw PV modules off roll cores and fabricating them into sheets ready for attachment of PC boards and lamination.

Figure 11. Parallel Taping Machine

This piece of hardware has been designed, fabricated and assembled and is shown in figure 11. On the left side, are the module feed stations where two rolls of bare PV sit side-by-side. There are also wind stations associated with these which are able to pick up an interleave layer that may be spooled in with the basic PV.

In the center of the picture you can see two independent tables (PV drawn up on the front one). These are vacuum belts which grab the PV and pull it off the spools. The modules are aligned side-by-side on the independent tables. Between the vacuum table and feed station there is a guillotine cutter that cuts the two modules to proper length. This can be seen along with the alignment camera which tells the machine where to cut the modules. Once the two strips of modules are pulled forward on the independent tables, the tables use machine vision to determine proper alignment and move the modules into proper position. The tables can adjust angular position as well as linear position for this alignment step.

The tape head can be see had seen hanging above the two tables. This head has a feed for conductive adhesive coated copper busbar and applies that busbar down the length joining the two modules and connecting them in series at the same time. The properly sized and taped modules are then moved downstream by the vacuum table to the next process step.

PC board Station The next station, shown in figure 12, is another vacuum belt to hold the module in place while the printed circuit board termination is placed and wired to the module through soldered jumpers.

Figure 12. Vacuum belt working table for placing the PC board and soldering on jumpers

Figure 13. Roll laminator and laminator infeed table. The module in the figure is getting an encapsulation layer on both top and bottom.

Roll based lamination and module feed station Once the PC board is mounted, the module moves forward again to the lamination station, shown in figure 13. The vacuum belt feed part of this station controls the timing of modules feeding into the roll laminator. In this way it becomes a buffer between the PC board station, which is step and repeat, and the laminator station which requires a constant speed. The top and bottom laminates are applied to the modules by the roll laminator to create the full weather seal.

Modules finished in this way then proceed to die cutter to be cut to size and then to the junction box assembly station where the strain release/junction box and external wiring are connected. For mounting on the tent, the final step is sewing Velcro onto the perimeter of the finished module.

Crates

Crates have been an issue over the years. Choices are a tradeoff between strength against rough handling, environmental durability and cost. We evaluated two styles of pre-fab plywood crates and a roto-molded plastic crate as options for the specifically fabricated particle board and wood frame crate we used in the past. The pre-fab plywood crates were both disqualified for physical drawbacks. One disassembled nicely for storage, but resulted in a group of small, loose parts which could be easily lost. The other, shown in figure 14 had sharp attachment flanges which protruded and could easily cause physical damage to people or the tents.

Figure 14. Quickcrate plywood prefab crate.

Figure 15. Rotomolded Crate

The roto-molded crate, shown in figure 15, was durable and weather resistant, but was expensive. Based on this evaluation, we are continuing to use the specifically fabricated wood crates as standard with the roto-molded crates as an option.

BOS system

The power actually taken from the Gen I PowerShade was limited by the BOS and power delivery system. To overcome this loss, a new BOS unit with higher power transfer efficiency has been developed. This system also has grid tie capabilities and options for operating in different modes.

Three modes of operation were identified and built into the new BOS system:

Mode 1 is mostly the same as the Gen I PowerShade, recharging the batteries from multiple powers sources and outputting Direct Current (DC) and Alternating Current (AC) with voltages that match DC and AC systems currently used by armed forces. The major difference is that it has a signal out to start and stop a backup Gen-set.

Mode 2 is a grid tie mode including battery storage, prioritizing battery storage as the highest priority. All available power beyond battery charging is dumped to the local grid. This grid may be as simple as a small single phase AC generator or as large as a military base grid with AC power from a local utility company.

Mode 3 is a grid tie connection without external battery storage. in this mode, all the available power from the solar array is dumped to the local grid.

Commercial off the shelf (COTS) components and modification of COTS components were evaluated in building the system. Maximum Power Point Tracking (MPPT) was implemented using a COTS MPPT controller. We also examined the abilities of COTS inverter units to bi-directionally transfer power to the batteries when connected to the grid. Electronics durability, radio frequency emissions, MPPT charge controller efficiency, inverter efficiency, operational temperature range, and environmental readiness were all taken into account when evaluating COTS units. After evaluation, we selected the Outback GTFX 2524 for the main inverter system.

Part of the BOS Grid Tie system development included testing commercial off the shelf inverters with standard Army Tactical Quiet Generators (TQG). We examined the grid tie inverters ability to tie up to a grid where frequency and voltage may vary more than the power provided by the power companies. Currently UL only allows inverters to attach to the grid when frequency doesn't vary more than +/- 1 Hz from 60Hz. UL requires that, if the frequency varies more than 1 Hz, then the Grid Tie inverter will unhook and not hook/tie until frequency returns to within specifications. Tests of the generator set provided by Natick showed less than expected variation. We setup and ran the generator at three different load levels to get the waveforms at each load. Measurements were taken at no load (less than 100 watts), both line to neutral (120V AC) and line to line (208V AC) waveforms were captured with a P5200A 50mHz High Voltage Differential Probe. Additional waveforms were taken at 7500 watts and 22000 watts. We found infrequent variation outside 1% and reasonable return to synchronization, so it appears that the COTS units will be usable without overriding the UL safety requirement.

Figure 16 shows the block diagram of three operating modes. The required functions of these operating modes are listed in the following table:

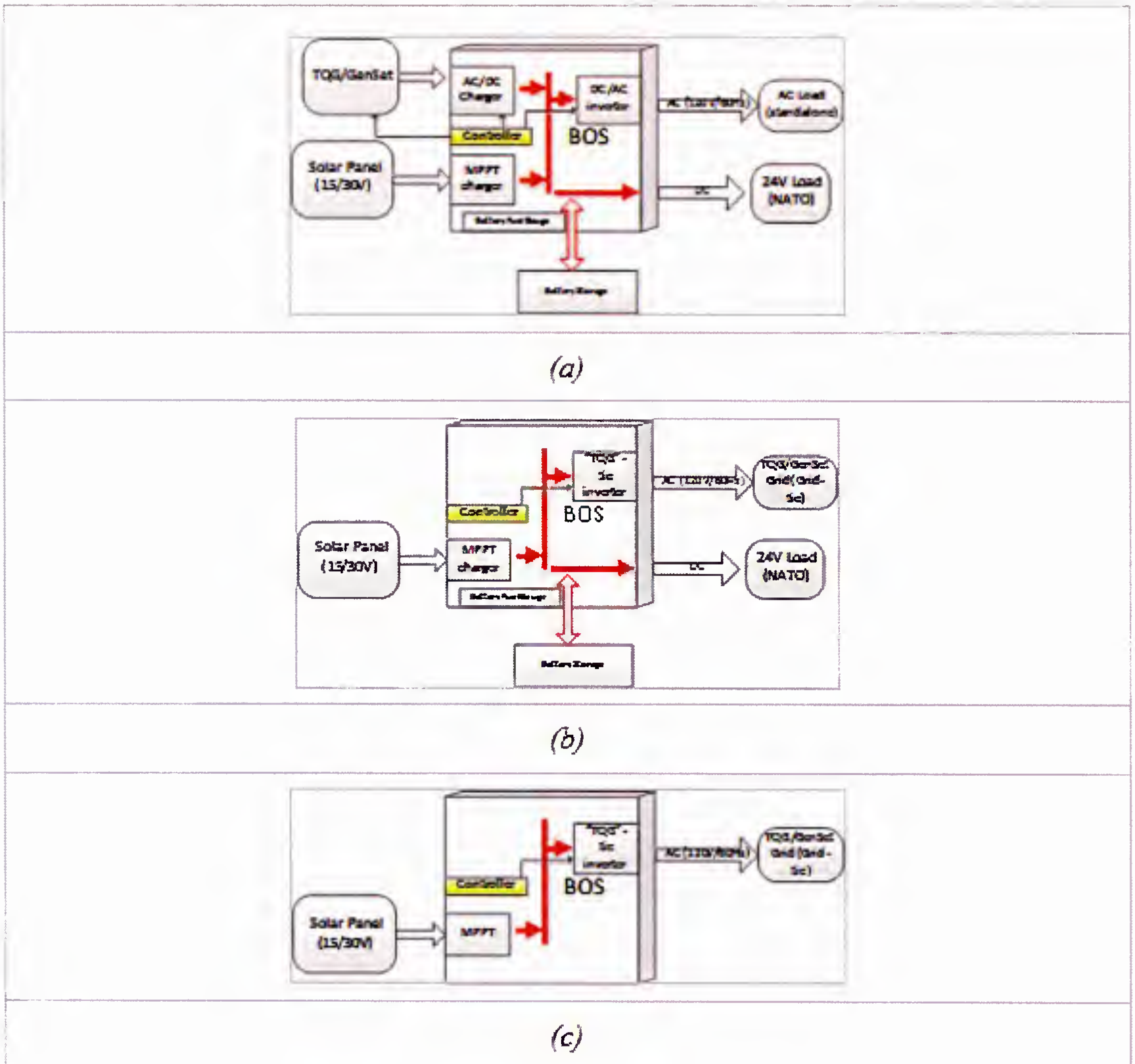


Figure 16. The block diagram of three operating modes: (a) Standalone with battery, (b) Grid tie with battery storage, (c) Grid tie without battery.

BOS Control Unit A microprocessor based control unit was developed to oversee the operation of the BOS. This control unit commands the COTS MPPT charge controller and Inverter through their operating bus along with the relays, indicator LED s and safety interlocks of the BOS. Outback provided us the command codes and protocols for their system to allow the proper interface. This microprocessor implements a control algorithm which is designed to optimize the power flow in the system so as to supply the load at lowest cost.

The hardware implementation was designed to make the whole system controllable by the software. The software is developed on a PC platform and then transferred to the microprocessor making upgrades easy. The software is designed as modules so that it could easily be modified to support the alternative Xantrex-based inverter system if needed. All the feasible BOS states were thoroughly analyzed; the PC software successfully controlled and configured Outback modules to desired operating states among the three proposed BOS operating modes. The software was designed following the concept of object oriented programming so that it could also easily adapted.

Main Software Flow Chart The main flow chart of the BOS software is shown in Fig. 17. The user selects the desired operating modes of the system through a switch. Because the battery is the main power source of the whole system, if no response from the user after start up, the system will be automatically setup in State 1, in which MPPT charger will try to charge the battery to maintain the necessary energy. The inverter is disabled under this condition due to safety considerations.

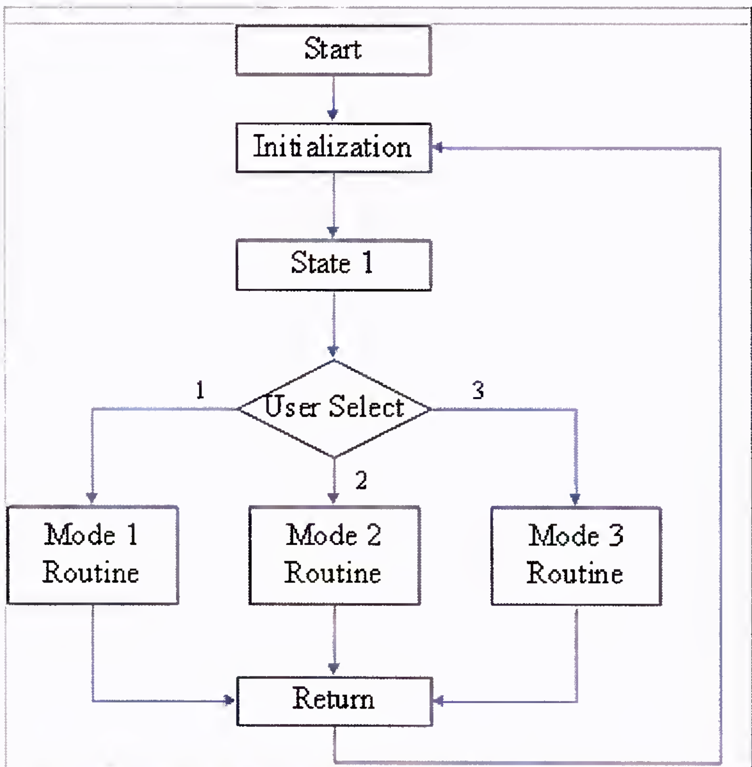


Figure 17. Top level flow chart of the BOS software

Control of Mode 1 In this mode, fulfilling the load demand has the highest priority. The software can turn on/off the TQG/Gen-set (if available) based on the solar energy yield, battery State of Charge (SOC), and load condition, so as to optimize the TQG usage. The grid output (selling) function of the inverter is disabled in this mode, so that the battery or PV energy cannot be sold to the AC grid.

Control of Mode 2 In this mode, the battery charging is the highest priority. After the battery voltage reaches a threshold, the surplus energy from PV can be sold to the grid (TQG/Gen-set). The software cannot turn on/off the TQG/Gen-set in this mode, but TQG/Gen-set should be always on. If the grid has a problem (fault), the inverter will be disabled so that the energy cannot be sold to the grid. Under the fault condition the system will enter State 1. Error messages will be displayed and user should manually reset the system to resume the routine of this mode.

Control of Mode 3 In this mode, the battery capacity is small and all solar energy is expected to be dumped into the grid. The software CANNOT turn on/off the TQG/Gen-set in this mode, but TQG/Gen-set should be always on. If the grid has problem (fault), the inverter will be disabled so that the energy cannot be sold to the grid. Under the fault condition the system will enter State 1. Error messages will be displayed and user should manually reset the system to resume the routine of this mode.

Mode 1 Optimization

Mode 1 is a special case because of its need for optimization in conjunction with a feeding TQG. While Modes 2 and 3 generally supplement a larger grid system and will mostly be dumping full power into the grid, Mode 1 needs to balance between load needs, battery storage and a backup TQG. It needs to do this in a manner to minimize fuel use in the TQG.

Due to the varying load patterns, the fluctuating solar energy acquired from the PV panels, and the resulting variation of battery SOC, the BOS power flow management controller should respond to continuously changing operating conditions. The objective is to select the most suitable combination of energy sources, power converters and energy storage system by the implementation of an efficient energy dispatch strategy, so as to reduce operation costs of the whole system.

Mode 1 can operate in 3 different scenarios.

- PV/Battery inverting

In this scenario TQG is turned off. This is the most desired scenario since no fuel consumption in TQG.

- Pass through

In this scenario TQG is turned on but the power from TQG is only feeding the AC loads, and the charging function of the inverter is purposely disabled.

- TQG charging

In this scenario TQG is turned on and the power from TQG is feeding both the battery storage and the AC loads, and the charging power from the inverter to the battery storage is assumed to be controllable.

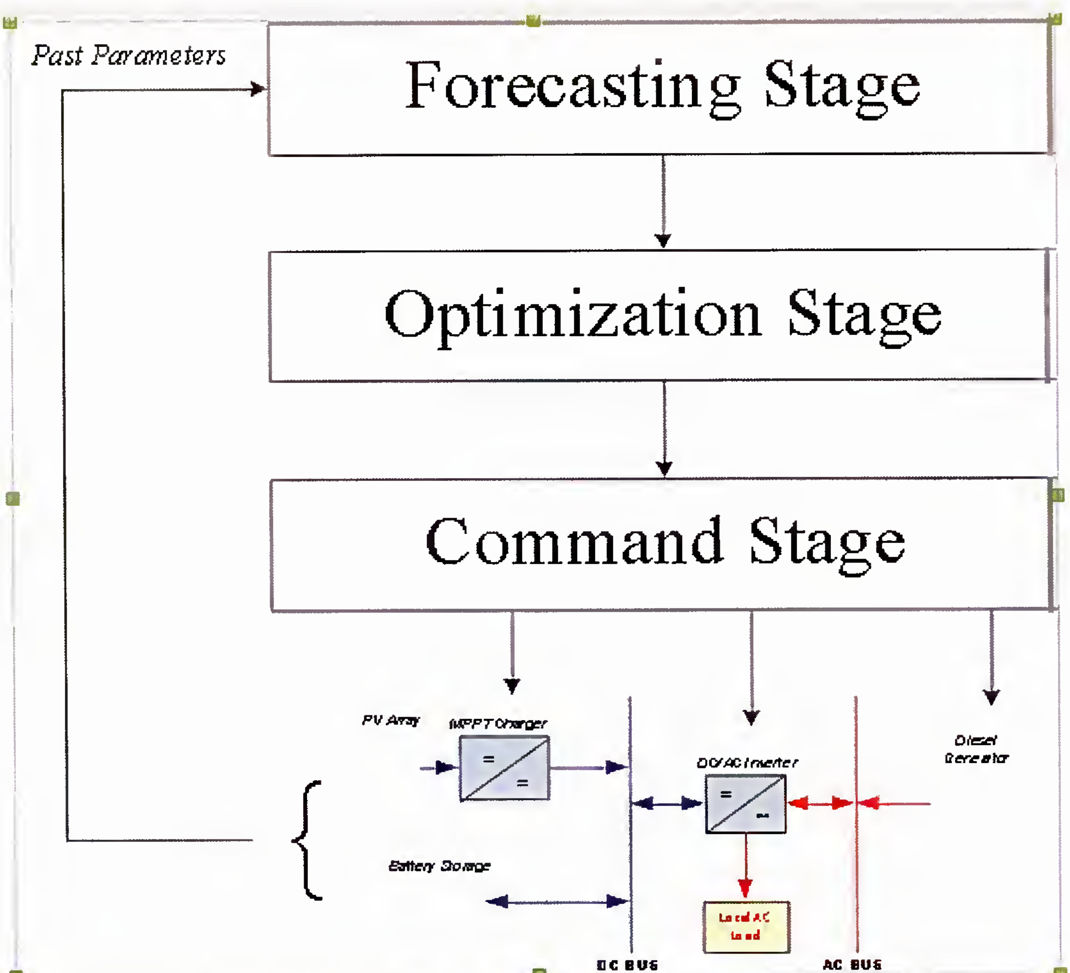


Figure 18. Structure of the power flow management supervisor

Fig. 18 illustrates the structure of the power flow management supervisor. It contains three hierarchy levels: the forecasting stage, the optimization stage and the command stage described as follows.

Forecasting Stage The system does not yet have forecasting capability, but has provisions for this function if developed in the future. Such a stage provides necessary parameters for the optimization stage. It will do two things:

- Forecasting AC loads profile based on past and prediction of the AC loads patterns.
- Forecasting PV energy generation based on the position, weather and existing solar irradiance database.

The more accurate the forecasts are, the better efficiency the power flow management can achieve. In the current system, the PV energy available and AC loads profile as fixed parameters.

Optimization Stage The purpose of the optimization stage is to find the power flow scheduling that minimizes the fuel consumption of TQG over a certain period. The input data of this stage (available PV energy, load profile) are from the forecasting stage and these parameters are considered as known.

The power flow management of BOS in Mode 1 is defined as the problem of finding an optimum loading pattern for each power component (MPPT charger, battery storage, DC-AC inverter, TQG) in each time period of a day in order to meet a given load.

In the optimization algorithm, the following constrains were considered:

- The system should continuously meet the load demand.
- The battery storage should not be charged (discharged) beyond the maximum (minimum)

Per these requirements, the problem is to find the optimal sequence of SOC transition from the initial time to the final time that achieves the final state from the initial state with the lowest fuel consumption. The flow chart for the rule-based algorithm to achieve this is shown in Fig. 19. The basic idea is: If PV and battery storage energy is enough, the load power is supplied by the PV energy and battery storage.

If the battery storage SOC reaches SOC_{min}, turn on the Gen-set to supply the load power. Let the system in pass through mode unless the load power is lower than P_{DG_min}.
The rule-based algorithm is practical and easy to implement.

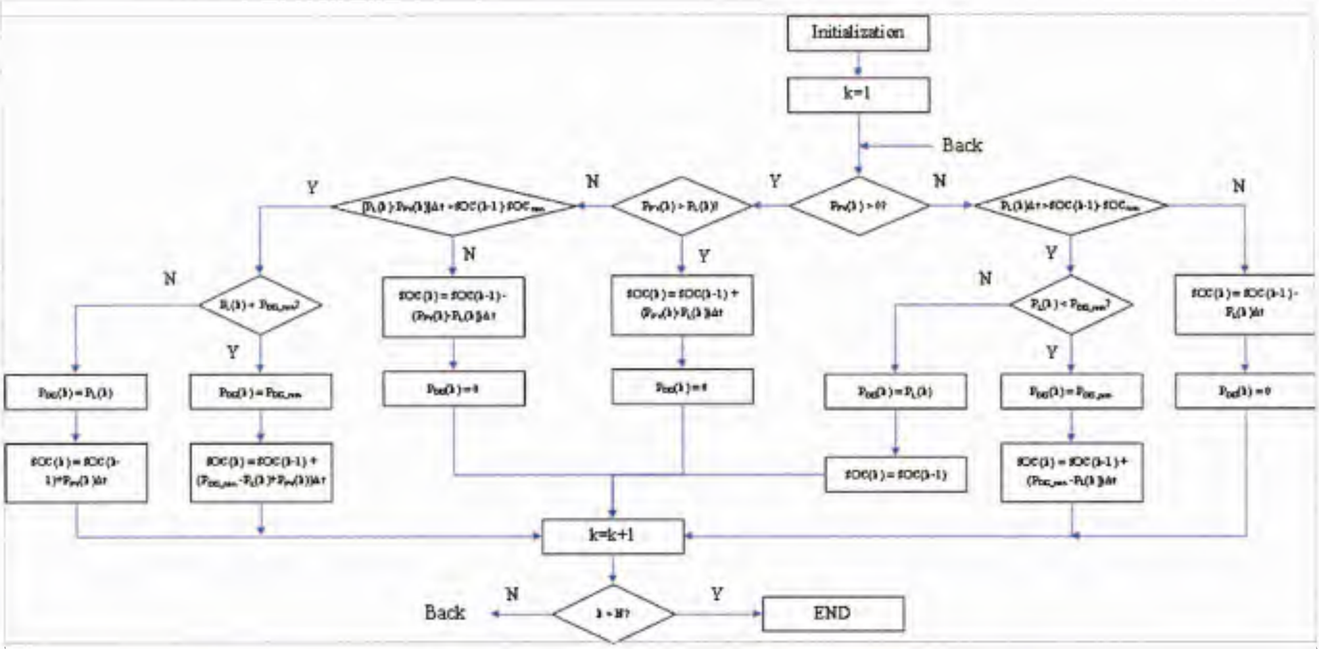


Figure 19. Flow chart for the rule-based algorithm to achieve optimum power use.

The rule-based algorithm has been simulated with the MATLAB software. The simulation was carried out for one 24 hour cycle of data. Results showed that the constrains can be satisfied with the designed rule-based algorithm implementation.

Command Stage The command stage is in charge of sending the proper commands to the power electronics converters (MPPT charger and DC-AC inverter) and turning on/off TQG, so as to fulfill the power flow schedule designed by the optimization stage.

Packaging

The components and wiring diagram of the BOS is shown in figure 20. For packaging of these components, it was decided to go with a Hardigg style case which offers a number of advantages and a few disadvantages. This style of case seems to be the standard within the military, they're available in quantity fairly quickly, and you can order them pre-machined for mounting hardware. They're not the cheapest; however volume does help with pricing. Mounting plates must be used, as the case isn't strong enough by itself for the inverter and charge controller. The aluminum case that is used for the Gen I BOS's is about twice as expensive due to a combination of effects outside Powerfilm's control. Given the lead time and availability of aluminum cases vs Hardigg case PF opted to build initial units from Hardigg cases. Battery boxes are also fabricated from Hardigg cases. These also require mounting plates for strength.

Figure 21 shows the completed and packaged BOS system while figure 22 shows the system with two battery boxes connected.

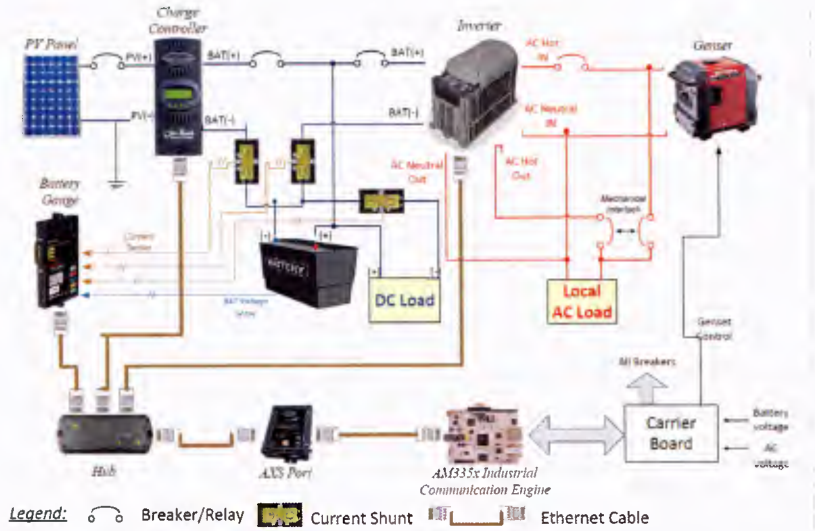


Figure 20. Wiring diagram for the BOS

Figure 21. Finished BOS system.

Figure 22. BOS system with two battery boxes connected.

Human Factors

The PowerShade is a large, moderately heavy structure and can be challenging to set up by hand. While the Gen I unit has been set up by as few as 2 people with judicious use of the ratchets, it is more commonly done with 8-10 people. We made a number of changes which improve the human factors on Gen II in addition to developing a system for use of a mechanical winch to pull the tent up.

The main changes which effect handling ease are:
1. Reduction of overall weight, though this is canceled out if the move is made to a bigger unit.
2. Moving to a slipperier fabric which slides more easily over itself and the ground, making folding and handling easier.
3. Moving to double-wide, stiffer modules which make folding easier and stacking squarer.
4. Reduction of the cross section of the poles which makes them easier to grip.
5. A slight reduction of the pole weight which makes moving and raising them easier.

In addition to the basic design changes, we have developed a method for using a winch to raise the first poles of the tent. This can be done with an optional rig and a vehicle mounted winch, a ground mounted power winch running off the BOS, or a manual "come-along". It uses pivot bases mounted on the front two poles and a harness attached to the front two straps. Figure 23 shows this system in operation with the tent partially raised.

Figure 23. Photo of a Gen II PowerShade being raised by an electrical winch (off to the left). There are pivot mounts on the bases of the two visible poles. The tent is then being pulled up while the winch and harness raise the poles.

Delivery of Tent Systems

Three Tents with BOS systems have been fabricated and sent To Natick to use in field tests. This pre-production run of 3 tents helped work some of the bugs out in the manufacturing process and identified other issues which will need to be addressed. Streamlining of the process for fabricating the Velcro attachment frames has helped throughput a great deal. The poles have many advantages over the previous design, however quality control issues will have to be addressed with the vendor or find an alternative fabricator.